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1. INTRODUCTION

Relationship between sea surface¹ temperature (SST) and cloud/water vapor reveals important information about radiative-climate feedbacks. Many previous studies have found that cloud amount and SST are positively correlated for SST between 28-29.5°C. For SST>29.5°C, cloud amount actually decreases with increasing SST. The breakdown of SST-cloud correlation at 29.5°C was suggested to be related to the formation of localized hot spots with very high SST due to increased solar radiation in regions of strong subsidence forced by convection elsewhere. In this study, the breakdown is related to the radiative cooling in the subsidence regime over the cold pool surrounding the warm pool. We show model and observational evidence that radiative cooling over the cold pool limits the strength of SST-induced tropical circulation. As a result, occurrence of convection is also limited when SST contrast between the warm pool and cold pool is large.

2. RESULTS

SST-convection relationship in the tropical deep convective regime and the surrounding subsidence regime is investigated in a cumulus ensemble model (CEM). The model is constrained by an imposed warm-pool and cold-pool SST contrast (dSST). The domain-mean vertical motion is also constrained to provide a heat sink and moisture source in the model to emulate the observed tropical climate condition. In a series of experiments, the warm pool SST is specified at different values while the cold pool SST is specified at 26°C. A circulation with mean ascending (descending) motion over the warm (cold) pool is developed in all experiments. The strength of the circulation increases with increasing dSST until dSST reaches 3.5°C (Exp. R to R1), and remains unchanged as dSST exceeds 3.5°C (Exp. R1 to R2). This can be explained by the change in heat budget in the subsidence regime

where radiative cooling changes little. For dSST<3.5°C, an enhanced subsidence warming is balanced by a reduced condensation heating. For dSST>3.5°C, the subsidence regime becomes too stable for condensation heating to occur so that a further enhanced subsidence warming can no longer be sustained.

The regulation of SST-induced circulation by radiative cooling affects the change of clouds as shown in the Table below. Clouds in the model are classified into three types: convective raining, stratiform raining, and stratiform non-raining, and their corresponding spatial coverage are denoted by A_{CR} , A_{SR} , and A_{SN} , respectively. The table shows that the change of active clouds (A_{CR+SR}) is closely related to the change of local circulation. For dSST<3.5°C (R1-R1), the enhanced circulation leads to an increase of A_{CR+SR} by 1.7% over the warm pool and a decrease of A_{CR+SR} by 2.6% over the cold pool. For dSST>3.5°C (R2-R1), circulation remains almost the same and the change of A_{CR+SR} is much weaker (-0.4% over the warm pool and 0.1% over the cold pool). Another important feature is the change of passive clouds (A_{SN}). Since A_{SN} consists of high clouds (above 500 hPa) originated from convective clouds, the change of A_{SN} is related to the change of active clouds in addition to the local circulation change. For dSST<3.5°C, A_{SN} over the cold pool increases by 4.5% despite the stronger downward motion, due to the increased A_{CR+SR} over the warm pool. The increase active clouds further lead to a decreased A_{SN} over the warm pool through enhanced mesoscale downdrafts. For dSST>3.5°C, the change of A_{SN} over the cold pool is significantly smaller (0.6%) due to the small change of circulation. In another experiment (W), the warm pool and cold pool temperature are specified 1°C warmer than those of R so the dSST remains at 2.5°C. The 4.4% increase of A_{SN} over the cold pool between W and R is apparently related to the increase of A_{CR+SR} over the warm pool. Finally, we note that total cloud amount (A_T) increases with increasing SST when dSST<2.5°C assuming the domain averaged circulation remains the same. This relation breaks down when dSST>2.5°C.

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Table Fractional area of clouds (%)

	Warm	Pool	Cold	pool	Total
	A_{CR+SR}	A_{SN}	A_{CR+SR}	A_{SN}	A_T
R1-R	1.7	-0.6	-2.6	4.5	3.0
R2-R1	-0.4	-0.3	0.1	0.6	-0.1
W-R	0.4	0.8	-1.9	4.4	3.8

To seek supporting evidence for the model results, we analyze monthly-mean values of high cloud amount (A_{HC}), total precipitable water (W), and vertical p-velocity (ω) as a function of SST. High cloud is derived from ISCCP D2 for the period July 1983 - August 1994 with a spatial resolution of $2.5^\circ \times 2.5^\circ$ longitude-latitude. Total precipitable water is derived over the oceans from measurements of the Special Sensor Microwave/Imager (SSM/I). The data are made of monthly mean quantities on $1^\circ \times 1^\circ$ longitude-latitude grid from July 1987 to December 1998. Vertical p-velocity is obtained from NCEP/NCAR data assimilation. The NCEP/NCAR has a horizontal resolution of $2.5^\circ \times 2.5^\circ$ longitude-latitude and available for 1949-1999 at present. The optimum interpolation SST is the merged ship and satellite. The SST is available on a T62 Gaussian grid ($\sim 1.87^\circ \times 1.87^\circ$ longitude-latitude). To be consistent with ISCCP D2 high cloud and NCEP/NCAR vertical velocity, the horizontal resolution of SSM/I precipitable water and SST is degraded to $2.5^\circ \times 2.5^\circ$ longitude-latitude by linear interpolation.

The tropical Pacific within 20°S - 20°N , 130°E - 110°W is chosen as our analysis domain. Within it, warm pool and cold pool is separated by an isotherm so determined that the area of warm pool is 25% of the analysis domain. There is a strong negative relation between cold pool SST and the corresponding SST contrast between the warm pool and cold pool (dSST) due to the ENSO evolution (figure not shown). There is also a weak positive relationship between warm pool SST and dSST, indicating the significant contribution by seasonal cycle in addition to the ENSO evolution.

A_{HC} over the warm (cold) pool appears to be positively (negatively) correlated with dSST for $dSST < 2.6^\circ\text{C}$. This correlation is related to the increased ascending (descending) motion over the warm (cold) pool associated with enhanced dSST. The correlation breaks down for $dSST > 2.6^\circ\text{C}$, consistent with the modeling results discussed above. A negative W -dSST relationship is found over the cold pool, as expected in the subsidence regime. However, W and dSST over the warm pool

appears to be negatively correlated. In comparison of the above analysis with model results, we note that, unlike the model experiments, the mean vertical motion in the domain of analysis varies and is expected to influence the SST-cloud/water vapor relationship. To further clarify the results, A_{HC} , W , and ω are shown in three categories of ω at 500 hPa: $(\omega - \omega_m) < -2 \text{ mbd}^{-1}$ (red), $|\omega - \omega_m| < 2 \text{ mbd}^{-1}$ (black), and $(\omega - \omega_m) > 2 \text{ mbd}^{-1}$ (blue), where ω_m is the time mean ω . The circulation-stratified A_{HC} and W as a function of dSST is consistent with model results.

We show the scatter plot of collocated A_{HC} and SST grid values for the months when $dSST > 2.7^\circ\text{C}$ and the months when $dSST < 2.2^\circ\text{C}$. The over relationship between SST and mean A_{HC} within each 0.2°C bin is well reproduced for the cases $dSST > 2.7^\circ\text{C}$, but not so for the cases $dSST < 2.2^\circ\text{C}$. This suggests that the breakdown of SST-cloud relationship at 29.5°C can be attributed to the regulation by radiative cooling in the large subsidence region over the cold pool.

3. CONCLUSION AND DISCUSSION

Our CEM experiments and observational analysis reveal a regulation mechanism of tropical convection by radiative cooling in the broad subsidence regime surrounding the warm pool. Warmer SST in the warm pool (and/or colder SST in cold pool) normally leads to increased occurrence of convection over the warm pool due to SST-induced circulation. This tendency breaks down when the SST gradient becomes large and sinking motion over the cold pool cannot increase anymore as constrained by radiative cooling. In such situation, the area ratio of cloudy area to clear area over the warm pool reduces to maintain mass and energy balance.

The change in area ratio between cloudy and clear areas in response to SST changes may have profound impact on radiation-climate feedback. In our CEM experiments, the change of water vapor and cloud greenhouse effect (G_{clear} , C_{LW}) per degree increase of dSST is about 8 Wm^{-2} and -2 Wm^{-2} , respectively, for $dSST < 3.5^\circ\text{C}$, and much smaller for $dSST > 3.5^\circ\text{C}$. In the case of uniform warming (W-R), the change of C_{LW} and G_{clear} per 1°C SST is about the same. Note that the change in G_{clear} is quite different among experiments, indicating the contribution of water vapor distribution over the cold pool.